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R-parity Violating Contribution to Neutron EDM at One-loop Order

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Abstract

We present the full result for the down squark mass-squared matrix in the complete theory of supersymmetry without R-parity where all kind of R-parity violating terms are admitted without bias. An optimal parametrization, the single-VEV parametrization, is used. The major result is a new contribution to LR squark mixing, involving both bilinear and trilinear R-parity violating couplings. Among other things, the latter leads to neutron electric dipole moment at one-loop level. Similar mechanism leading to electron electric dipole moment at the same level. We present here a short report on major features of neutron electric dipole moment from supersymmetry without R-parity and give the interesting constraints obtained.

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Introduction. The minimal supersymmetric standard model (MSSM) is no doubt the most popular candidate theory for physics beyond the Standard Model (SM). The alternative theory with a discrete symmetry called R-parity not imposed deserves no less attention. A complete theory of supersymmetry (SUSY) without R-parity, where all kind of R-parity violating (RPV) terms are admitted without bias, is generally better motivated than *ad hoc* versions of RPV theories. The large number of new parameters involved, however, makes the theory difficult to analyze. It has been illustrated [1] that an optimal parametrization, called the single-VEV parametrization, can be of great help in making the task manageable. Here in this letter, we use the formulation to present the full result for the down squark mass-squared matrix. The major result is a new contribution to *LR* squark mixing, involving both bilinear and trilinear RPV couplings. The interesting physics implications of this new contribution are discussed. Among such issues, we focus here on the RPV contribution to neutron electric dipole moment (EDM) at one-loop level.

Neutron and electron EDM's are important topics for new CP violating physics. Within MSSM, studies on the plausible EDM contributions lead to the so called SUSY-CP problem [2]. In the domain of R-parity violation, two recent papers focus on the contributions from the trilinear RPV terms and conclude that there is no contribution at the 1-loop level [3]. Perhaps it has not been emphasized enough in the two papers that they are *not* studying the complete theory of SUSY without R-parity. It is interesting to see in the latter case that there is in fact contribution at 1-loop level, as discussed below. We would like to emphasize again that the new contribution involves both bilinear and trilinear (RPV) couplings. Since various other RPV scenarios studied in the literature typically admit only one of the two types of couplings, the contribution has not been previously identified.

The most general renormalizable superpotential for the supersymmetric SM (without R-parity) can be written as

$$W = \varepsilon_{ab} \left[\mu_\alpha \hat{H}_u^a \hat{L}_\alpha^b + h_{ik}^u \hat{Q}_i^a \hat{H}_u^b \hat{U}_k^C + \lambda'_{\alpha jk} \hat{L}_\alpha^a \hat{Q}_j^b \hat{D}_k^C \right. \\ \left. + \frac{1}{2} \lambda_{\alpha\beta k} \hat{L}_\alpha^a \hat{L}_\beta^b \hat{E}_k^C \right] + \frac{1}{2} \lambda''_{ijk} \hat{U}_i^C \hat{D}_j^C \hat{D}_k^C, \quad (1)$$

where (a, b) are $SU(2)$ indices, (i, j, k) are the usual family (flavor) indices, and (α, β) are extended flavor index going from 0 to 3. In the limit where $\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}$ and μ_i all vanish, one recovers the expression for the R-parity preserving case, with \hat{L}_0 identified as \hat{H}_d . Without R-parity imposed, the latter is not *a priori* distinguishable from the \hat{L}_i 's. Note that λ is antisymmetric in the first two indices, as required by the $SU(2)$ product rules, as shown explicitly here with $\varepsilon_{12} = -\varepsilon_{21} = 1$. Similarly, λ'' is antisymmetric in the last two indices, from $SU(3)_C$.

R-parity is exactly an *ad hoc* symmetry put in to make \hat{H}_d stand out from the other \hat{L}_i 's. It is defined in terms of baryon number, lepton number, and spin as, explicitly, $\mathcal{R} = (-1)^{3B+L+2S}$. The consequence is that the accidental symmetries of baryon number and

lepton number in the SM are preserved, at the expense of making particles and superparticles having a categorically different quantum number, R-parity. The latter is actually not the most effective discrete symmetry to control superparticle mediated proton decay [4], but is most restrictive for term admitted in the superpotential.

Doing phenomenological studies without specifying a choice of flavor bases is ambiguous. It is like doing SM quark physics with 18 complex Yukawa couplings, instead of the 10 real physical parameters. As far as the SM itself is concerned, the extra 26 real parameters are simply redundant, and attempts to relate the full 36 parameters to experimental data will be futile. In SUSY without R-parity, the choice of an optimal parametrization mainly concerns the 4 \hat{L}_α flavors. Under the SVP, flavor bases are chosen such that : 1/ among the \hat{L}_α 's, only \hat{L}_0 , bears a VEV, *i.e.* $\langle \hat{L}_i \rangle \equiv 0$; 2/ $h_{jk}^e (\equiv \lambda_{0jk}) = \frac{\sqrt{2}}{v_0} \text{diag}\{m_1, m_2, m_3\}$; 3/ $h_{jk}^d (\equiv \lambda_{0jk} = -\lambda_{j0k}) = \frac{\sqrt{2}}{v_0} \text{diag}\{m_d, m_s, m_b\}$; 4/ $h_{ik}^u = \frac{v_u}{\sqrt{2}} V_{\text{CKM}}^T \text{diag}\{m_u, m_c, m_t\}$, where $v_0 \equiv \sqrt{2} \langle \hat{L}_0 \rangle$ and $v_u \equiv \sqrt{2} \langle \hat{H}_u \rangle$. The big advantage of here is that the (tree-level) mass matrices for *all* the fermions *do not* involve any of the trilinear RPV couplings, though the approach makes *no assumption* on any RPV coupling including even those from soft SUSY breaking; and all the parameters used are uniquely defined, with the exception of some removable phases. In fact, the (color-singlet) charged fermion mass matrix is reduced to the simple form :

$$\mathcal{M}_c = \begin{pmatrix} M_2 & \frac{g_2 v_0}{\sqrt{2}} & 0 & 0 & 0 \\ \frac{g_2 v_u}{\sqrt{2}} & \mu_0 & \mu_1 & \mu_2 & \mu_3 \\ 0 & 0 & m_1 & 0 & 0 \\ 0 & 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & 0 & m_3 \end{pmatrix}. \quad (2)$$

Readers are referred to Ref. [1] for details concerning the RPV effects on the leptons.

Squark mixing and EDM. The soft SUSY breaking part of the Lagrangian can be written as follows :

$$\begin{aligned} V_{\text{soft}} = & \epsilon_{ab} B_\alpha H_u^a \tilde{L}_\alpha^b + \epsilon_{ab} \left[A_{ij}^U \tilde{Q}_i^a H_u^b \tilde{U}_j^c + A_{ij}^D H_d^a \tilde{Q}_i^b \tilde{D}_j^c + A_{ij}^E H_d^a \tilde{L}_i^b \tilde{E}_j^c \right] + \text{h.c.} \\ & + \epsilon_{ab} \left[A_{ijk}^{\lambda'} \tilde{L}_i^a \tilde{Q}_j^b \tilde{D}_k^c + \frac{1}{2} A_{ijk}^\lambda \tilde{L}_i^a \tilde{L}_j^b \tilde{E}_k^c \right] + \frac{1}{2} A_{ijk}^{\lambda''} \tilde{U}_i^c \tilde{D}_j^c \tilde{D}_k^c + \text{h.c.} \\ & + \tilde{Q}^\dagger \tilde{m}_Q^2 \tilde{Q} + \tilde{U}^\dagger \tilde{m}_U^2 \tilde{U} + \tilde{D}^\dagger \tilde{m}_D^2 \tilde{D} + \tilde{L}^\dagger \tilde{m}_L^2 \tilde{L} + \tilde{E}^\dagger \tilde{m}_E^2 \tilde{E} + \tilde{m}_{H_u}^2 |H_u|^2 \\ & + \frac{M_1}{2} \tilde{B} \tilde{B} + \frac{M_2}{2} \tilde{W} \tilde{W} + \frac{M_3}{2} \tilde{g} \tilde{g} + \text{h.c.}, \end{aligned} \quad (3)$$

where we have separated the R-parity conserving ones from the RPV ones ($H_d \equiv \hat{L}_0$) for the A -terms. Note that $\tilde{L}^\dagger \tilde{m}_{\tilde{L}}^2 \tilde{L}$, unlike the other soft mass terms, is given by a 4×4 matrix. Explicitly, $\tilde{m}_{L_{00}}^2$ is $\tilde{m}_{H_d}^2$ of the MSSM case while $\tilde{m}_{L_{0k}}^2$'s give RPV mass mixings.

We have illustrated above how the SVP keeps the expressions for the down-quark and color-singlet charged fermion mass matrices simple. The SVP performs the same trick to

the corresponding scalar sectors as well. Here, we concentrate on the down-squarks. We have the mass-squared matrix as follows :

$$\mathcal{M}_D^2 = \begin{pmatrix} \mathcal{M}_{LL}^2 & \mathcal{M}_{RL}^{2\dagger} \\ \mathcal{M}_{RL}^2 & \mathcal{M}_{RR}^2 \end{pmatrix}, \quad (4)$$

where \mathcal{M}_{LL}^2 and \mathcal{M}_{RR}^2 are the same as in MSSM while

$$(\mathcal{M}_{RL}^2)^T = A^D \frac{v_0}{\sqrt{2}} - m_D \mu_0^* \tan\beta - (\mu_i^* \lambda'_{ijk})_* \frac{v_u}{\sqrt{2}}. \quad (5)$$

Here, m_D is the down-quark mass matrix, which is diagonal under the parametrization adopted; $(\mu_i^* \lambda'_{ijk})_*$ denotes the 3×3 matrix $(\)_{jk}$ with elements listed; and $\tan\beta = \frac{v_u}{v_0}$. Note that in the equation for $(\mathcal{M}_{RL}^2)^T$, we can write the first, A -term, contribution as

$$A^D \frac{v_0}{\sqrt{2}} = A_d m_D + \delta A^D \frac{v_0}{\sqrt{2}} \quad (6)$$

with A_d being a constant (mass) parameter representing the “proportional” part. The remaining terms in $(\mathcal{M}_{RL}^2)^T$ are F -term contributions; in particular, the last term is a “SUSY conserving” [5] but R-parity violating contributions given here for the first time. In fact, contributions to LR scalar mixing of this type, for the sleptons, is first identified in a recent paper [6] where their role in the SUSY analog of the Zee neutrino mass model [7] is discussed. In a parallel paper by one of the authors (O.K.) [8], a systematic analysis of the full squark and slepton masses as well as their contributions, through LR mixings, to 1-loop neutrino masses are also presented. Here, we focus only on the down-quark sector. Note that the full F -term part in the above equation can actually be written together as $(\mu_\alpha^* \lambda'_{\alpha jk})_* \frac{v_u}{\sqrt{2}}$ where the $\alpha = 0$ term gives the second term in RHS of Eq.(5), which is the usual μ -term contribution in the MSSM case. The latter is, however, diagonal, *i.e.* vanishes for $j \neq k$. We would like to emphasize that the above result is complete — all RPV contributions are included. The simplicity of the result is a consequence of the SVP. Explicitly, the RPV A -terms contributions [*c.f.* Eq.(6)] vanish as $v_i \equiv \sqrt{2} \langle \hat{L}_i \rangle = 0$

The $(\mu_i^* \lambda'_{ijk})_*$ term is very interesting. It involves only parameters in the superpotential and has *nothing to do with soft SUSY breaking*. Without an underlining flavor theory, there is no reason to expect any specific structure among different terms of the matrix. In particular, the off-diagonal terms ($j \neq k$) may have an important role to play. They contribute to flavor changing neutral current (FCNC) processes such as $b \rightarrow s \gamma$, a topic to be addressed in a later publication [9]. Moreover, both the μ_i ’s and the λ'_{ijk} ’s are complex parameters. Hence, diagonal terms in $(\mu_i^* \lambda'_{ijk})_*$ also bear CP-violating phases and contribute to electric dipole moments (EDM’s) of the corresponding quarks. In particular, $\mu_i^* \lambda'_{i11}$ gives contribution to neutron EDM at 1-loop level, in exactly the same fashion as the A -term in MSSM does. The similar term in LR slepton mixing gives rise to electron EDM. This result is in direct

contrary to the impression one may get from reading the two recent papers on the subject [3]. One should bear in mind that the two papers do not put together both the bilinear and the trilinear RPV terms. Our treatment here, bases on the SVP, gives, for the first time, the result of squark masses for the complete theory of SUSY without R-parity. Going from here, obtaining the EDM contributions is straight forward.

Contribution to EDM of the d quark at 1-loop level, from a gaugino loop with LR -squark mixing in particular (see Fig. 1), has been widely studied within MSSM [2,10–12]. With the squark mixings in the down-sector parametrized by δ_{jk}^D (normalized by average squark mass as explicitly shown below), we have the neutron EDM result given by

$$d_n = -\frac{8}{27} \frac{e \alpha_s}{\pi} \frac{M_{\tilde{g}}}{M_{\tilde{d}}^2} \text{Im}(\delta_{11}^D) F_1\left(\frac{M_{\tilde{g}}^2}{M_{\tilde{d}}^2}\right) \quad (7)$$

where $M_{\tilde{g}}$ and $M_{\tilde{d}}$ are the gluino and down squark masses respectively, and

$$F_1(x) = \frac{1}{(1-x)^3} \left(\frac{1+5x}{2} + \frac{2+x}{1-x} \ln x \right) . \quad (8)$$

Contribution of $\mu_i^* \chi_{i11}$ to δ_{11}^D is to be given as

$$-\mu_i^* \chi_{i11} \frac{v_u}{\sqrt{2}} \frac{1}{M_{\tilde{d}}^2} .$$

Requiring the contribution alone not to upset the experimental bound on neutron EDM : $(d_n)^{\text{exp}} < 6.3 \cdot 10^{-26} e \cdot \text{cm}$, a bound can be obtained for the RPV parameters. Note that going from d quark EDM to neutron EDM, we assume the simple valence quark model [13]. Taking $M_{\tilde{d}} = 100 \text{ GeV}$ and $M_{\tilde{g}} = 300 \text{ GeV}$ gives the bound

$$\text{Im}(\mu_i^* \chi_{i11}) \leq 10^{-6} \text{ GeV} , \quad (9)$$

(with $v_u \sim 200 \text{ GeV}$). This result is interesting. Let us first concentrate on the $i = 3$ part, assuming the $i = 1$ and 2 contribution to be subdominating. Imposing the 18.2 MeV experimental bound [14] for the mass of ν_τ still admits a relatively large μ_3 , especially for a large $\tan\beta$. Reading from the results in Ref. [1], the bound is $\sim 7 \text{ GeV}$ at $\tan\beta = 2$ and $\sim 300 \text{ GeV}$ at $\tan\beta = 45$, while the best bound on the corresponding χ_{311} (from $\tau \rightarrow \pi\nu$) is around $0.05 \sim 0.1$ [15].

Here, an explicit comparison with the corresponding R-parity conserving contribution is of interest. From Eqs.(5) and (6), it is obvious that we are talking about $(A_d - \mu_0^* \tan\beta) m_d$ verses $-\mu_i^* \chi_{i11} \frac{v_u}{\sqrt{2}}$. Both A_d and μ_0 are expected to be roughly at the same order as v_u , *i.e.* at electroweak scale. We are hence left to compare m_d ($\sim 10^{-3} \text{ GeV}$) with $\mu_i^* \chi_{i11}$. The above discussion then leads to the conclusion that the RPV part could easily be larger by one or even two orders of magnitude.

On the other hand, if one insists on a sub-eV mass for ν_τ as suggested, but far from mandated, by the result from the Super-Kamiokande (super-K) experiment [16], we would have $\mu_3 \cos\beta \leq 10^{-4} \text{ GeV}$ [17]. This means that at least for the large $\tan\beta$ case, the EDM bound as given by Eq.(9) still worths notification, even under this most limiting scenario.

The $\mu_i^* \lambda'_{i11}$ contribution to squark mixing, as well as λ'_{i11} in itself together with an A -term mixing, also gives rise to neutrino mass at 1-loop. Hence, to consistently impose the super-K sub-eV neutrino mass scenario, one should also check the corresponding bound obtained. We are interested here in whether these will further weaken the implication of the EDM bound discussed here. Fig. 2 shows a familiar quark-squark loop neutrino mass diagram. We are interested here in the case where both the λ' -couplings are λ'_{311} . We have, for the R-parity conserving LR squark mixing, the familiar result

$$m_{\nu_\tau} \sim \frac{3}{8\pi^2} m_d^2 \frac{(A_d - \mu_0^* \tan\beta)}{M_{\tilde{d}}^2} \lambda'_{311} . \quad (10)$$

However, with the full LR mixing result as given in Eq.(5), there is an extra contribution to be given as

$$\frac{3}{8\pi^2} m_d \frac{v_u}{\sqrt{2}} \frac{\mu_i^* \lambda'_{i11}}{M_d^2} \lambda'_{311}^2 . \quad (11)$$

The latter type of RPV contribution to neutrino masses has not been identified before (see however Refs [6] and [8]).

From Eq.(10), one can easily see that the requirement for m_{ν_τ} to be at the super-K atmospheric neutrino oscillation scale only gives a bound for λ'_{311} of about the same magnitude as one quoted above, from the other sources. As for the contribution [Eq.(11)], the bound given by Eq.(9) itself says the contribution is smaller than the previous one. Hence, neutrino mass contributions from Fig. 2 do not change our conclusion above.

Note that the EDM bound given by Eq.(9) actually involves a summation over index i . Results from Ref. [1] indicated that while μ_1 is very strongly bounded, the bound on μ_2 could be not very strong. Moreover, the bound on λ'_{211} is no better than that on λ'_{311}^2 [15]. Hence, the EDM bound may still be of interest there too. The story for imposing the super-K constraint is obviously the same as the above discussion for the $i = 3$ case.

One should bear in mind that the EDM and the neutrino mass bounds involve different combinations of RPV parameters as well as with the other SUSY parameters. An exact comparison for bounds obtained from the two sources is hence difficult. Our discussion above is aimed at illustrating the fact that the EDM bound is not completely overshadowed by the super-K neutrino mass bound. In other word, even requiring the magnitudes for the RPV parameters to satisfy the most stringently interpreted super-K bounds does not make them so small that the above discussed contribution to neutron EDM will always be satisfied.

Beyond the gluino diagram. Similar RPV contributions on the neutron and electron EDM's are obtained through neutralino exchange diagram. One simply has to replace the gluino in the diagram with the other neutral gauginos. In the neutron case, the gluino diagram contribution discussed here no doubt dominate, due to the much stronger QCD coupling.

There are other 1-loop contributions. In the case of MSSM, the chargino contribution is known to be competitive or even dominates over the gluino one in some regions of the parameter space [10]. The major part of the chargino contribution comes from a diagram with a gauge and a Yukawa coupling for the loop vertices, with pure L -squark running in the loop. Here we give the corresponding formula generalized to the case of SUSY without R-parity. This is given by [18]

$$\left(\frac{d_f}{e}\right)_{\chi^-} = -\frac{\alpha_{\text{em}}}{4\pi \sin^2 \theta_W} \sum_{\tilde{f}'^\mp} \sum_{n=1}^5 \text{Im}(\mathcal{C}_{fn\mp}) \frac{M_{\chi_n^-}}{M_{\tilde{f}'^\mp}^2} \left[\mathcal{Q}_{\tilde{f}'} B\left(\frac{M_{\chi_n^-}^2}{M_{\tilde{f}'^\mp}^2}\right) + (\mathcal{Q}_f - \mathcal{Q}_{\tilde{f}'}) A\left(\frac{M_{\chi_n^-}^2}{M_{\tilde{f}'^\mp}^2}\right) \right], \quad (12)$$

for f being u (d) quark and f' being d (u), where

$$\begin{aligned} \mathcal{C}_{un\mp} &= \frac{y_u}{g_2} \mathbf{V}_{2n}^* \mathcal{D}_{d1\mp} \left(\mathbf{U}_{1n} \mathcal{D}_{d1\mp}^* - \frac{y_d}{g_2} \mathbf{U}_{2n} \mathcal{D}_{d2\mp}^* - \frac{\lambda'_{i11}}{g_2} \mathbf{U}_{(i+2)n} \mathcal{D}_{d2\mp}^* \right), \\ \mathcal{C}_{dn\mp} &= \left(\frac{y_d}{g_2} \mathbf{U}_{2n} + \frac{\lambda'_{i11}}{g_2} \mathbf{U}_{(i+2)n} \right) \mathcal{D}_{u1\mp} \left(\mathbf{V}_{1n}^* \mathcal{D}_{u1\mp}^* - \frac{y_u}{g_2} \mathbf{V}_{2n}^* \mathcal{D}_{u2\mp}^* \right). \end{aligned} \quad (13)$$

The terms in $\mathcal{C}_{dn\mp}$ with only one factor of $\frac{1}{g_2}$ and a λ'_{i11} gives the RPV analog of the dominating MSSM chargino contribution. The term is described by a diagram, which at first order requires a $l_{L_i}^- \tilde{W}^+$ mass mixing. The latter vanishes, as shown in Eq.(2). From the full formula above, it is easy to see that the exact mass eigenstate result would deviate from zero only to the extent that the mass dependence of the B and A functions [18] spoils the GIM like cancellation in the sum. The resultant contribution, however, is shown by our exact numerical calculation to be substantial. What is most interesting here is that an analysis through perturbational approximations illustrates that the contribution is proportional to, basically, the same combination of RPV parameters, *i.e.* $\mu_i^* \lambda'_{i11}$. While we cannot give much of the details here (see Ref. [18]), let us list numbers from a sample point for illustration : with $A_u = A_d = 500$ GeV, $\mu_0 = -300$ GeV, $\tan\beta = 3$, a common gaugino masses at 300 GeV, $\tilde{m}_Q = 200$ GeV, $\tilde{m}_u = \tilde{m}_d = 100$ GeV, $\mu_3 = 1 \times 10^{-4}$ GeV, and $\lambda'_{311} = 0.1 \times \exp(i\pi/6)$ (being the only complex parameter), we have the resulted neutron EDM contributions from gluino, chargino(-like), and neutralino(-like) 1-loop diagrams given by 2.49, 0.56, and -0.056 times $10^{-27} e \text{ cm}$, respectively.

Summary. In summary, we have presented the complete result for LR squark mixing and analyzed its contribution to neutron EDM through the gluino diagram. The result provide interesting new bounds on RPV parameters. A brief discussion for the chargino(-like) 1-loop

contribution is also given, together with a sample result from exact numerical calculations, including also the neutralino(-like) loop. The full details will be report in an publication.

We would also like to mention that there is the analogous case for the slepton mixing and electron EDM. The latter contributions, while having a similar structure, has potential complications from mixings with charged Higgs. The issue is under investigation.

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Figure captions :

Fig. 1 — EDM for d quark at 1-loop.

Fig. 2 — Neutrino mass at 1-loop.

FIGURES

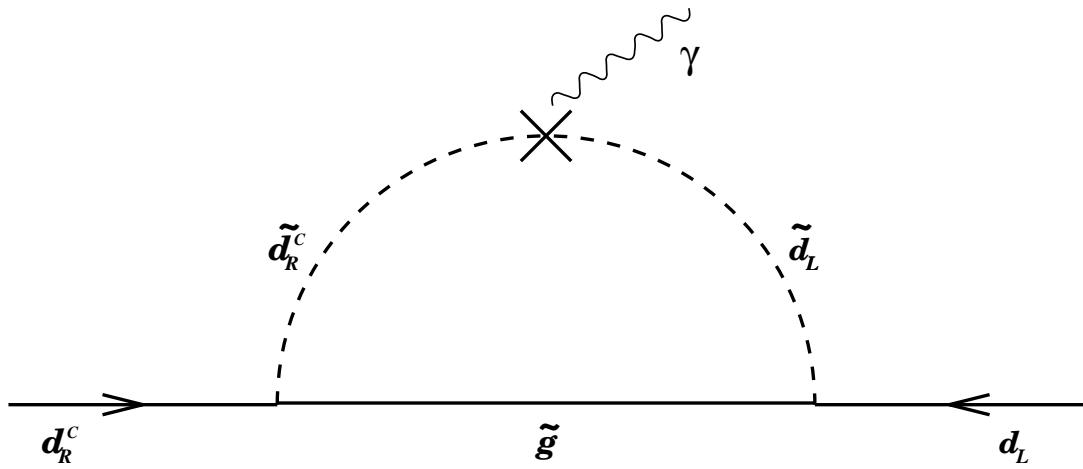


FIG. 1. EDM for d quark at 1-loop.

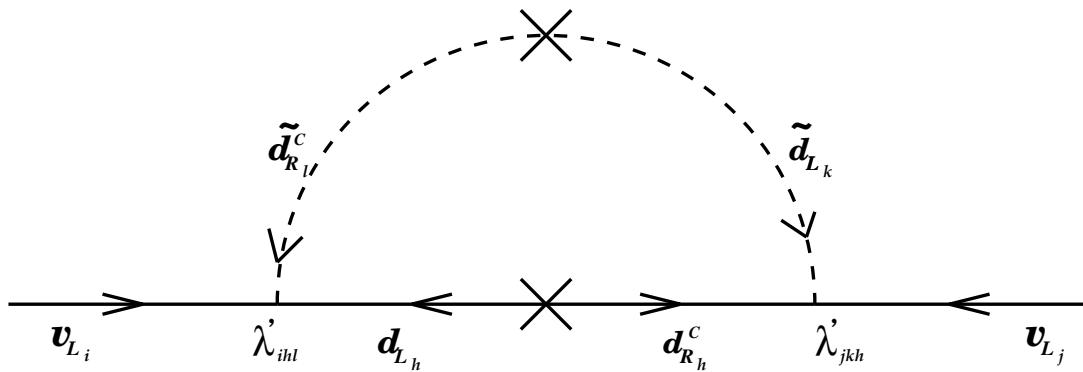


FIG. 2. Neutrino mass at 1-loop.